# Packaged inline cascaded optical micro-resonators for multi- parameter sensing

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**Abstract** - A novel design principle and fabrication method for whispering gallery mode optical multiple-resonator arrays have been proposed and demonstrated. The proposed design involves an inline cascade of optical micro-resonators (ICOMRs) coupled to multiple tapered sections along a single optical fiber. The multiple micro-resonators can be used for sensing of several parameters or a single parameter at multiple locations simultaneously. A simple and robust packaging technique has been developed ensuring stable and repeatable operation of the device. In order to demonstrate the capability of simultaneous multi- parameter sensing of the proposed ICOMRs structure, strain and temperature measurements were carried out using an inline cascade of two cylindrical micro-resonators: a tapered polymer optical fiber based micro-cylinder and a polydimethylsiloxane coated silica cylindrical micro-resonator. An Axial tensile strain sensitivity of 1.4±0.04 pm/με and temperature sensitivity of 330±18 pm/ºC have been demonstrated experimentally. The proposed ICOMRs design has many potential applications in distributed sensing, lab-on-a-fiber technology and optical communications.

***Keywords*: Whispering gallery modes, Microcavity devices, Fiber optics sensors, Multisensor methods.**

## I. Introduction

Multiplexing of whispering gallery mode (WGM) micro-resonators has been a field of extensive research for almost three past decades. There have been numerous planar integrated multiple ring resonator devices developed for various applications including optical add/drop multiplexers in optical communications [1-4], optical delay lines [5-7], devices for management of dispersion and pulse distortion [8, 9] *etc*. Free-space WGM microresonators have also become a popular choice in many applications after J. C. Knight *et al.* showed in 1997 that high-Q WGMs could be easily and efficiently excited in micro-spherical resonators by an adiabatic optical fiber taper [10]. Other than tapered fiber coupling to a single free space micro-resonator, other coupling schemes, often involving multiple resonators, have been considered for various applications. For example, a study of induced transparency and absorption was performed using two coupled microspheres in [11]; optical pulse propagation experiments were reported with two coupled microspheres of different sizes for demonstrating the classical analogy of extremely slow light in [12]; high-Q WGMs in two coupled spheres were used to calculate optically induced attractive and repulsive forces in [13] and an optical waveguide design was reported using chains of dielectric microspheres in [14]. More recently, a theoretical study of a serially-coupled double microsphere system was carried out with the objective of reducing the number of non-fundamental resonances and achieve higher resonant frequency spacing [15]. However, the above structures suffer disadvantages such as increased attenuation and limited fabrication tolerances.

An experimental study of multi-resonators coupled by a single tapered fiber for optical sensing application was for the first time reported by F. Vollmer *et al*. [16]. In their study, a sensor structure with two spherical microresonators coupled to the waist portion of a single tapered fiber was used for multiplexed DNA detection and to discriminate a single nucleotide. M. Sumetsky *et al.* [17] reported a similar structure using double liquid core optical ring resonators to fabricate a temperature and pressure compensated microfluidic optical sensor. Multi parameter sensing using such kind of structures, where microresonators is closely packed on a single fiber taper is challenging. Therefore, to isolate each resonator they need to be separated and so require individual tapered fibers. Furthermore, achieving optimal phase matching for more than one micro-resonator with the same waist diameter taper is difficult. These results in a limit on the number of micro-resonators in an array with the consequence that such structures had been rarely explored for multi-parameter sensing even though WGM sensors could offer very high measurement resolution due to their high-quality factors, low mode volumes and the high sensitivity of WGMs to external perturbations. In this article we for the first time propose a novel design principle for an inline cascaded optical micro-resonators (ICOMRs). A simple and robust fabrication method for the ICOMRs structure has also been developed and is demonstrated experimentally for simultaneous sensing of strain and temperature.

## II. Fabrication of the proposed ICOMRs

The proposed ICOMRs approach involves fabrication of several tapered sections along the length of a single fiber for coupling of several optical micro-resonators. Evanescent light fields surrounding the fabricated tapered sections of the fiber are utilized for exciting WGMs in the individual resonators. It should be noted that each tapered fiber section is coupled to a single resonator only to allow for the appropriate selection of the diameter of each tapered section so as to achieve phase matching with its corresponding resonator for maximal coupling efficiency. The resulting transmission spectrum of the tapered fiber contains combined WGM spectra for the entire cascade of coupled resonators, so that multiple micro-resonators can be used for sensing of several parameters simultaneously or sensing of parameters at multiple locations. Since the losses within the untapered portions of the fiber are relatively low, the distances between the cascaded inline resonators have negligible effect on the overall transmission spectrum. The proposed cascaded inline system of coupled micro-resonators offers a quasi-distributed measurement capability along the length of the coupling fiber, whose length could be varied in principle from a few centimeters to several kilometers. A useful packaging technique is also proposed to make the device mechanically stable. The potential applications of the ICOMR are in multi-parametric and distributed sensing, in studies of sensors' cross-sensitivity, for lab-on-a-fiber technology, in optical coding and the design and fabrication of optical logic gates *etc*.

The micro-resonators in our experiments were prepared from short sections of a standard coating-stripped silica fiber (SMF-28) and a polymer optical fiber (POF). The choice of the cylindrical structure as a resonator geometry in our study is due to its simplicity of fabrication and due to the fact that the alignment for optimal coupling of the excitation light with the cylindrical resonator depends on only one angular degree of freedom, as opposed to two for experiments involving microspheres. In practice the original diameters of SMF-28 and POF (125 μm and 490 μm respectively) would result in a very small free spectral range (FSR), but larger FSRs are desired for achieving wide measurement ranges for sensors based on such WGM resonators. Thus, in order to reduce the diameters of the source fibers used for the resonators down to more suitable values, the original commercial fibers were tapered using a customised micro-heater tapering setup [18].

## III. Initial Feasibility Experiments

As an initial feasibility experiment, a number of similar cylindrical silica microresonators were fabricated and then coupled and packaged with a single multi-taper fiber and subsequently the resulting spectral characteristics were investigated. The purpose of this experiment was not to demonstrate multi-parameter sensing but rather to show that coupling could take place to multiple resonators and that the spectral dips of the individual resonators are distinguishable.

Firstly, as an illustration of the proposed packaging method for an ICOMRs, Fig. 1 (a-c) shows schematically the main fabrication steps for a cascade of three inline resonators. As a first step of the packaging process, shown in Fig. 1 (a), the prepared micro-cylinders (MR1, MR2, and MR3) are attached on to three different glass substrates at a height of ~1 mm above the glass surface using a UV- curable glue. The lengths of all three microcylinders were ~20 mm. The tapered optical fiber used for coupling was fabricated using the same fiber tapering setup used for the SMF-28 based micro-cylinder diameter reduction. Next, to fabricate a triple ICOMR, three tapered portions (Taper-1, Taper-2, and Taper-3) are fabricated along the length of a single optical fiber, as shown in Fig. 1 (b). The total length of the silica fiber was about 2 meters. Tapering of the silica fiber down to diameter of 1.3 μm at three different positions results in the overall loss of 3.6 dB (measured after the tapering).

In order to attain critical coupling between the fabricated tapered optical fiber and the cylindrical micro-resonator, distances between the fiber taper and micro-resonator for each of the pairs shown in Fig. 1 (a) & (b) were adjusted manually using a translation stage with an adjustable 3D-positioner. Using the vertical positioner, the micro-cylinder was brought in contact with the tapered fiber to excite the WGMs. It should be noted that due to the difficulty in manipulating the thin and fragile tapered silica fibers, this step was carried out while the corresponding portion of the fiber containing the tapered section was still secured horizontally between the two translation stages of the taper-drawing setup after its fabrication. The two ends of the tapered fiber were connected to a super luminescent diode (SLD) (Thorlabs) with a wavelength range of 1500–1600 nm and an optical spectrum analyzer (OSA) (Advantest, Q8384) with a resolution of 0.01 nm. To maximize the light coupling strength, the micro-cylinder must be placed orthogonally and in direct physical contact with the fiber taper waist. After achieving the physical contact with the tapered fiber, as explain in [10], the value of the fiber taper diameter required for an efficient excitation of the fundamental WGM can be determined from the phase matching condition between the propagation constant of the WGM at the surface of the resonator and the propagation constant of the appropriate mode in the tapered fiber. In our experiment we achieved the required phase matching by slowly moving the micro-cylinder along the taper axis using a micro-translation stage while maintaining physical contact and a mutually orthogonal orientation, until the coupling point corresponded to the optimal value of the taper diameter for phase matching as described in [19]. During this process, the transmission spectrum of the taper was observed at the OSA screen to determine the optimal position of the contact point, corresponding to the phase match between the propagating mode of the fiber taper and the fundamental WGM of the micro-cylinder. The extinction ratio of the WGMs can be maximize by tuning the input light polarization. After achieving the desired WGM spectrum quality, both ends of the tapered fiber were glued to the glass substrate using a UV curable epoxy as shown in Fig. 1 (c). The same steps were repeated with the other two micro-cylinder-tapered fiber portions.

In the transmission spectrum of such an array of WGM micro-resonators each resonator must have its own unique family of spectral dips. Therefore, during the second and third resonator coupling steps, spectral overlaps of WGMs due to the previously coupled resonators must be avoided. This can be achieved by either using resonators with deliberately different diameters fabricated by the tapering process or alternatively relying on the fact that the limitations of the tapering process means that tapers with slightly different diameters are naturally generated anyway, typically differences are less than one micron which is sufficient to ensure adequate spectral separation. Figure 1 (c) is a schematic of a packaged triple-cylindrical resonator array. The robustness of the packaged system was confirmed by testing the device in the presence of strong vibrations by placing it on a mechanical vibration generator as explained in [20]. Figure 2 shows the photograph of an ICOMR formed by three cylindrical microresonators.

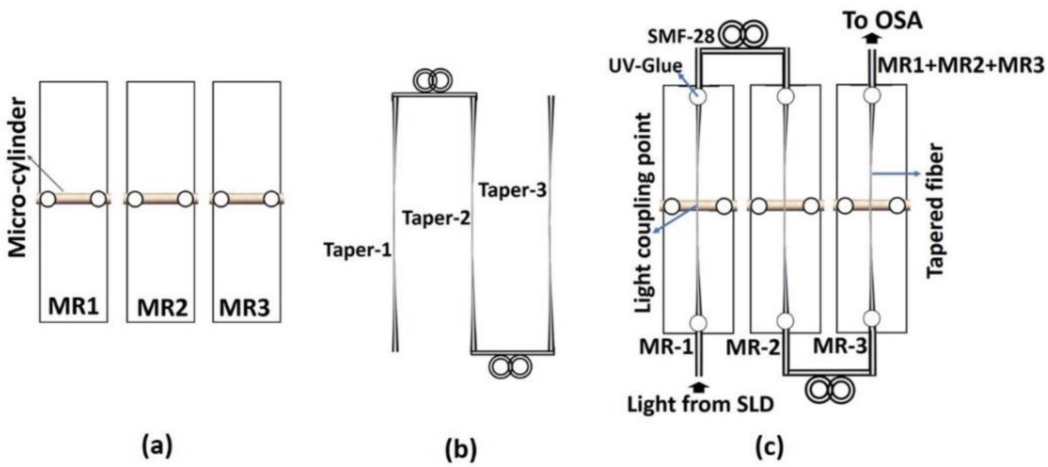


**Fig. 1**. Schematic diagrams illustrating the ICOCR packaging steps: (a) cylindrical microresonators attached to glass substrates; (b) three tapered sections fabricated along the single optical fiber and (c) packaged ICOMR formed by three resonators.

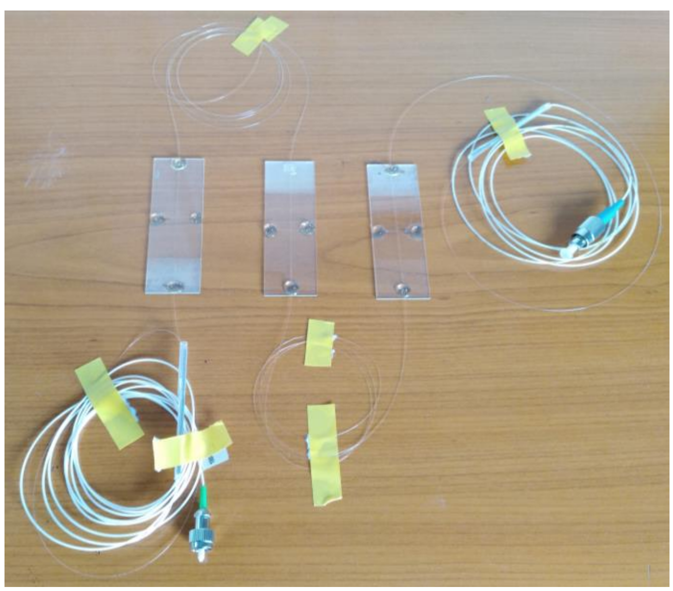

**Fig. 2**. Photograph of an ICOMR formed by three cylindrical micro-resonators.

Finally, the spectral characteristics of the fabricated ICOMRs are investigated. Figures 3 (a) & (b) show the WGM spectra for the different packaged ICOMRs, illustrating their additive nature. Figure 3 (a) shows the WGMs observed in the transmission spectrum of the double ICOMR. In Fig. 3 (a), the individual WGM spectra and that for an ICOMR formed by two cylindrical micro-resonators with slightly different external dimeters around 20 µm.  The difference in diameter for the two resonators is a natural result of the limitations of the tapering process, as mentioned earlier. Figure 3 (b) shows the WGM spectra for the individual cylindrical micro-resonators in an ICOMR formed by three cylindrical micro-resonators with slightly different external diameters around 15 μm and the resulting composite ICOMR spectrum.

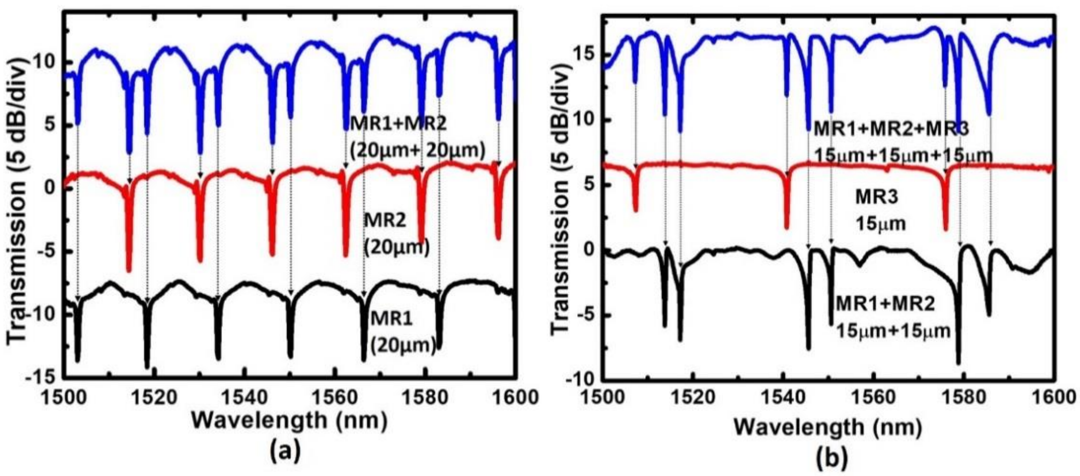


**Fig. 3**. Transmission spectra for ICOCRs formed by (a) two ~ 20 μm diameter resonators and (b) three ~ 15 μm diameter resonators. Each graph illustrates the individual and combined WGM spectra.

## IV. Multi-parameter sensing using ICOMRs

In order to demonstrate sensing of different parameters simultaneously at multiple locations using the proposed ICOMRs structure, a new experimental ICOMRs was fabricated using a polydimethylsiloxane (PDMS) coated silica micro-resonator and a tapered POF micro-resonator, following the method illustrated in Fig. 1 (a-c). The PDMS coated silica micro-resonator and the tapered POF micro-resonator served for temperature and strain measurements respectively. PDMS material was chosen for the coating of the silica micro-cylinder due to its low attenuation loss, good chemical stability and large thermo-optic coefficient [21], while a POF micro-cylinder was chosen for strain sensing because of its large elastic modulus compared to silica fibers [20, 22, 23].

The PDMS coating was prepared as a solution with a base to curing agent ratio of 5:1. Coating a 10 μm diameter silica microcylinder with the prepared PDMS solution resulted in a bottle-shaped structure [24], in effect a cylinder with a distinct bulge toward the cylinders centre point, most probably due to the viscosity and the surface tension of the applied solution. A photo of the structure using an optical microscope is shown in Fig. 4. After application of the coating, the micro-resonator was cured at 80 ºC for 30 minutes and then at room temperature (20 to 26 ºC) for further 24 hours. The WGM spectrum resulting from coupling to the bulge equator showed densely spaced high Q-factors modes but was highly sensitive to mechanical vibrations and thus was deemed not suitable for packaging. A more stable spectrum resulting from coupling to the neck of the bottle was selected for further packaging of the resonator. The thickness of the PDMS coating layer at the neck region was estimated using optical microscopy to be circa 3.36 μm. The Q-factor of the modes was estimated as $1.1\times10^4$.

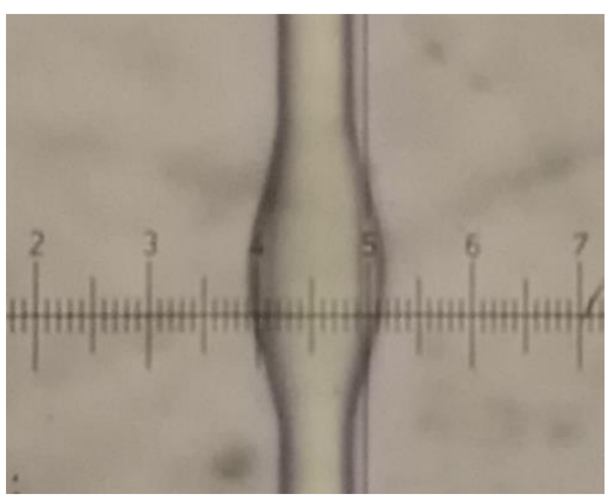


**Fig. 4**. Optical microscope image of PDMS coated microfiber. One division of the scale in the image is equaling to 1.67 μm.

A POF microfiber with a diameter of circa 15 µm was prepared by heat and pull technique from a standard POF (GPOF 62, Thorlabs) of 490 µm diameter. The Q-factor of the resonant modes due the tapered POF cylindrical microresonator was $7\times10^2$. Packaging of the strain sensor based on the POF tapered micro-cylinder was achieved as explained in [20]. Figure 5 shows the WGM spectra excited by the individual resonators (PDMS-coated and POF) as well as the resulting combined ICOMR spectrum.

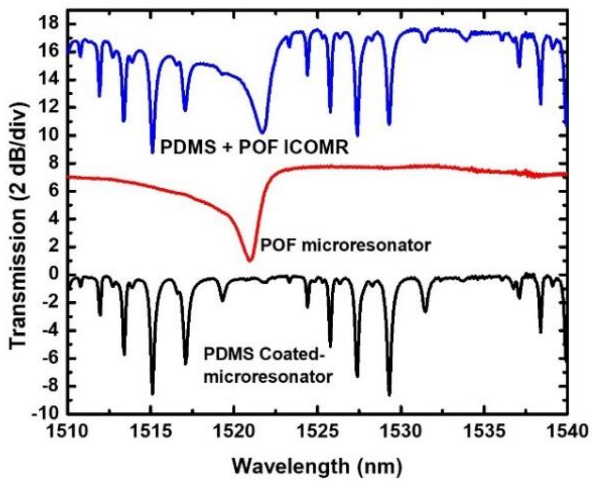


**Fig. 5.** WGM spectra for the PDMS-coated micro-resonator, POF micro-resonator and the resulting ICOMRs.

After the ICOMR fabrication, a series of experiments was carried out by placing the two sensors circa one meter apart from each other. The one-meter separation was chosen to demonstrate that sensing can not only take place for two different physical quantities but also at two different points. The PDMS-coated resonator was mounted at the top of a temperature-controlled hot stage, and its temperature was gradually increased from room temperature (25 °C) to 45ºC in 2ºC steps. The temperature of the hot stage was measured by a thermocouple with a 0.1ºC measurement resolution. Tensile strain was applied to the POF micro-resonator by axial elongation with a step of 0.01 mm using a translation stage with a resolution of 10 µm as explained in [20, 22]. To avoid the influence of temperature on the POF micro-resonator it was placed inside an environmental chamber maintaining constant room temperature, facilitated also by the 1-meter separation of the sensors. The sensing length of the POF micro-resonator was 70 mm (the distance between two fixed ends). The resulting spectral changes were recorded using an OSA.

Figure 6 shows the experimental transmission spectra of this ICOMR recorded at different increasing temperatures and strains applied to the respective micro-resonators. In the figure, one of the groups of WGM troughs associated with the PDMS-coated silica micro-resonator is labelled 'PDMS-WGM' and the resonant trough due the POF micro-resonator is marked as 'POF-WGM'. It can be seen from the figure that an increase in temperature results in a blue shift of the PDMS-WGM troughs and an increase the applied axial strain also leads to a slight blue shift of the 'POF-WGM' spectral dip.

In more detail, Fig. 7 (a) & (b) illustrate the measured dependences of the spectral positions of selected WGM resonances associated with each of the micro-resonators as functions of the applied axial strain and temperature with the corresponding linear fittings. The PDMS-WGM troughs experienced a total spectral blue shift of 6.47 nm within the given temperature range resulting in estimated sensitivity of 330±18 pm/ºC. By way of justification, the large blue shift for the PDMS-WGMs is likely due to the large negative thermo-optical coefficient of the PDMS material ($-1.8\times10^{-4}$) [21]. The POF-WGM experienced a total spectral shift of 0.99 nm within the studied tensile strain range from 0 to 714 µε with a sensitivity of 1.4±0.04 pm/µε due to the combined effect of the decrease in diameter and changes in the refractive index of the resonator as explained in [20, 22, 23]. As mention in [25], the operational range of PDMS coated microresonator based temperature sensor is limited to −50 to 200 °C [25] and from our experience the maximum applied strain to the tapered POF based strain sensor is about 2000 µε.

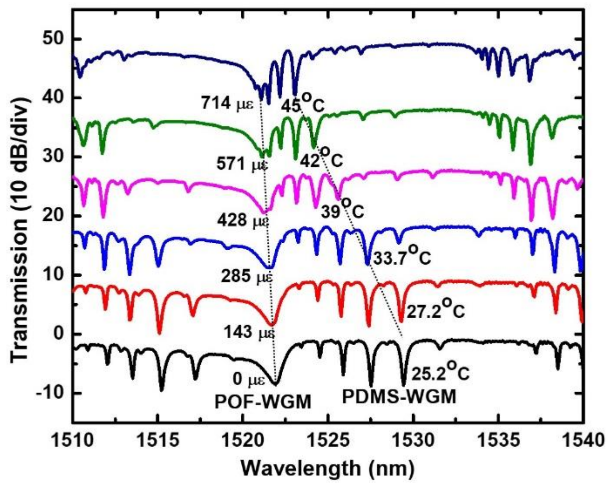


**Fig. 6.** Transmission spectra of the ICOMR at different temperatures and applied strain values.

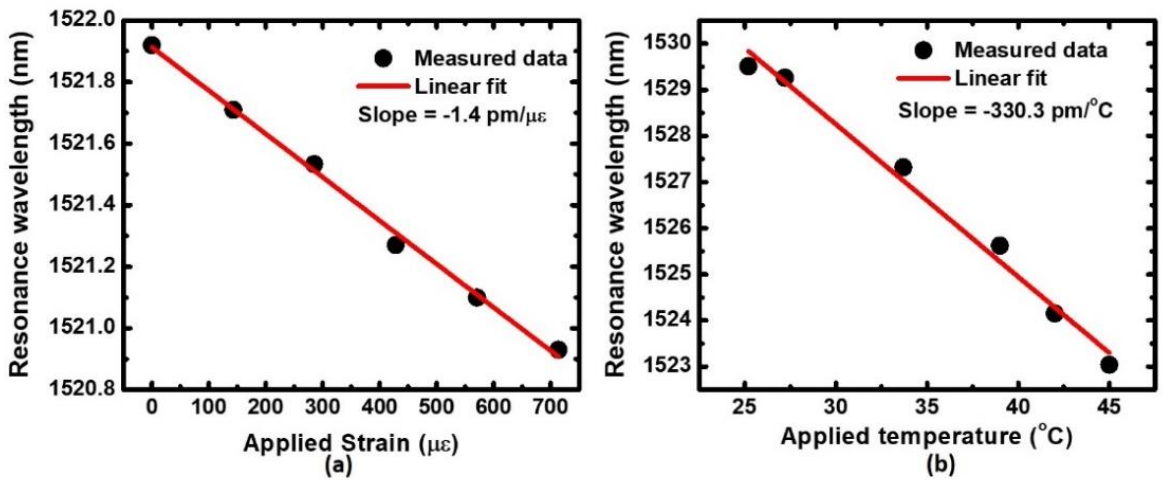


**Fig. 7**. Spectral shift of selected resonance troughs for (a) POF micro-cylinder vs. applied strain and (b) PDMS-coated silica micro-cylinder vs temperature.

## V. Conclusions

In summary, an ICOMR coupled to a single optical fiber with multiple tapered sections has been proposed and demonstrated for the first time. Evanescent fields from the various tapered portions along the fiber are used to excite the WGMs in the corresponding individual micro- resonators. The inline cascade of multiple "resonator-tapered fiber" pairs has an output transmission spectrum where the families of WGM spectral dips produced by each of the individual coupled resonators can be clearly observed. Fabrication of the tapered fibers and micro-cylinders was carried out by the micro-heater brushing technique. The proposed packaging technique provides mechanical stability and makes the device more portable. To demonstrate multi-parameter sensing using the proposed ICOMR structure, simultaneous measurements of strain and temperature were carried out for an ICOMR formed by POF based and PDMS-coated silica cylindrical micro-resonators. An axial tensile strain sensitivity of 1.4±0.04 pm/με and a high temperature sensitivity of 330±18 pm/ºC were demonstrated. This initial study indicates that the proposed inline resonator structure is promising for many photonic applications such as distributed sensing, cross-sensitivity studies, lab-on-a fiber technology, optical coding and optical logic gates, etc.

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